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ORIGINAL RESEARCH

Effect of wearing an N95 filtering facepiece respirator on superomedial orbital infrared indirect brain temperature measurements

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Abstract To determine any effect of wearing a filtering facepiece respirator on brain temperature. Subjects ($n = 18$) wore a filtering facepiece respirator (FFR) for 1 h at rest while undergoing infrared thermography measurements of the superomedial periobital region of the eye, a non-invasive indirect method of brain temperature measurements we termed the superomedial orbital infrared indirect brain temperature (SOIIBT) measurement. Temperature of the facial skin covered by the FFR, infrared temperature measurements of the tympanic membrane and superficial temporal artery region were concurrently measured, and subjective impressions of thermal comfort obtained simultaneously. The temperature of the skin under the FFR and subjective impressions of thermal discomfort both increased significantly. The mean tympanic membrane temperature did not increase, and the superficial temporal artery region temperature decreased significantly. The SOIIBT values did not change significantly, but subjects who switched from nasal to oronasal breathing during the study ($n = 5$) experienced a slight increase in the SOIIBT measurements. Wearing a FFR for 1 h at rest does not have a significant effect on brain temperatures, as evaluated by the SOIIBT measurements, but a change in the route of breathing may impact these measurements. These findings suggest that subjective impressions of thermal discomfort from wearing a FFR under the study conditions are more likely the result of local dermal sensations rather than brain warming.

Keywords Filtering facepiece respirators · Thermal discomfort · Orbital infrared indirect brain temperature measurements

1 Introduction

A frequent complaint voiced by a substantial number of users of protective facemasks (e.g., filtering facepiece respirators [FFR], medical/surgical masks, etc.) regards thermal discomfort that is manifested as subjective impressions of increases in facial warmth or total body heat [1–3]. This is an important issue given that thermal intolerance to protective facemasks impacts compliance and, by extension, protection [3]. Prior investigations have demonstrated that increases in core body temperature (T_{core}) associated with wearing these devices are minimal (<0.13 °C) over 1–2 h at low-moderate work rates, and thus unlikely to be a major stimulus for thermal intolerance [4, 5]. Potential pathways for perceptions of increased heat include warming of the facial skin that is covered by the protective facemask or brain warming [3]. Facial skin is very thermosensitive and a portion of the face covered by protective facemasks (i.e., the lips, vermillion cutaneous border) is especially dense in sensory receptors [6], so that increases in the temperature of protective facemask-covered facial skin may result in increased trigeminal nerve afferent sensory impulses conducted to the brain [7]. Alternatively, research by Cabanac et al. [8] has suggested

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that brain temperature (as indicated by tympanic membrane temperature), rather than other deep body T_{core}, is the major determinant of thermal comfort in humans. It has been postulated that some protective facemask-associated thermal discomfort sensations could be related to warming of the anterior portion of the brain by rebreathing of warmed, humidified exhaled air retained within the deadspace of the protective facemask [4]. Studies of post-operative neurosurgical patients with thermal sensors implanted in brain tissue have documented the effect of nasal airflow on temperatures of the brain's frontal lobes and hypothalamic region [9, 10]. Therefore, it seems possible that nasal inhalation of rebreathed warmed, humidified air from a protective facemask might have a warming effect on brain structures and resulting thermal discomfort. However, the invasive nature of implanted temperature sensors in the brain relegates their use to neurosurgical interventions or animal studies. Brain tissue is in thermal equilibrium with its surrounding venous blood [11], and a portion of the brain's venous drainage (superficial middle cerebral vein and inferior cerebral veins [12]) empties into the cavernous sinus that also receives flow from the superior ophthalmic vein (SOV). The lack of valves in the dural sinuses, cerebral veins and SOV (in a majority of instances) allows blood to flow in either direction according to pressure gradients in the vascular system [13, 14]. The SOV thus serves as a thermal conduit for the temperature of the cavernous sinus blood that is in equilibrium with brain tissue [14]. Noninvasive dermal temperature sensors, placed over the passage [termed the brain temperature tunnel (BTT)] encompassing the SOV in the superomedial orbit region of the eye and coursing between the orbit and the cavernous sinus, offer a site for core temperature measurement [15]. Infrared thermography (IRT) studies have demonstrated that the site of origin of the SOV, the thin, fat-free skin of the superomedial orbit area of the face, emits more infrared energy than any other facial area [16, 17] and could thus serve as an indirect, non-invasive measure of brain temperature. The current study was undertaken by the National Personal Protective Technology Laboratory of the National Institute for Occupational Safety and Health (NIOSH) to evaluate the use of superomedial orbital infrared indirect brain temperature (SOIIBT) measurements as an alternative to invasive brain temperature monitoring. The object of the study was to determine if brain warming occurs with wearing FFR, the most commonly used respirators in U.S. industry and healthcare.

2 Materials and methods

Eighteen healthy subjects (9 men, 9 women) were enrolled in the study. Subject demographic mean values for men were age 23 ± 1.6 years, height 182 ± 7.7 cm, weight 78.3 ± 9.4 kg, and body mass index (BMI) 23.6 kg/m^2; for women, these values were age 21.5 ± 1.5 years, height 164.1 ± 5.3 cm, weight 61.9 ± 5.2 kg, and BMI 22.8 ± 2.5 kg/m^2. Subjects were examined by a licensed physician immediately prior to engaging in the study. During trials (carried out during the winter months in the northern hemisphere), subjects wore standard clothing and were seated upright in a physiology laboratory with mean ambient temperature 24.2 ± 2.6 °C and mean relative humidity (RH) 20.5 ± 5.5 %. Natural and artificial light were minimized to reduce any reflected or direct light impact on IRT measurements [18]. A FLIR Model SC 5600-M High Resolution cooled, infrared camera (FLIR Systems, Inc., North Billerica, MA) was utilized for the study and positioned 1½ m from the subject's face [19]. The camera focused on the region of interest ipsilateral to the dominant brain hemisphere side that was determined by the subjects' right or left handedness (17 subjects were right-handed) [20]. Camera emissivity was set at 0.98 and, based upon differences in the sizes of the regions of interest, a ~1:5 ratio of minimum pixels was utilized for recordings of the dominant superomedial canthus area (208 pixels) (Fig. 1a) and the dominant superficial temporal artery region (1020 pixels) [21] (Fig. 1b). Maximum SOIIBT measurements and superficial temporal artery area dermal temperatures were identified in real time (2 s recordings at a recording frame rate of 60 Hz) using a fluctuating histogram plot on FLIR-specific software (Research IR^{TM}). A flat-fold surgical N95 FFR (SN95 FFR), model 3M 1870 (3M Company, St Paul, MN), was outfitted with a small wireless sensor (iButton, Dallas, TX) attached with adhesive to its inner surface for measurement of respirator deadspace temperature and RH. The iButton sensors are calibrated against a National Institute of Standards and Technology (NIST) traceable source. An identical sensor was attached to the subject's perioral skin area of the dominant brain side to capture temperatures of the skin covered by the SN95 FFR. Respiratory rate (RR) was measured with the BioHarness 3^{TM} (Zephyr Technology Corporation, Annapolis, MD), a physiological monitoring chest strap [22]. Baseline IRT measurements of the dominant side superomedial orbit area and the superficial temporal artery region (Fig. 1), as well as tympanic membrane temperatures, were obtained after the subjects were seated for 10 min in the physiology laboratory to allow for adaptation to room temperature [23]. The SN95 FFR was then donned, as per the manufacturer's recommendation, and the same measurements were repeated at 30 and 60 min of SN95 FFR wear. Anatomic areas of subjective impressions of facial warmth were documented with the use of a facial mannequin placard with numbered anatomic landmarks (Fig. 2). Subjective scoring of thermal comfort of facial skin areas was obtained using the

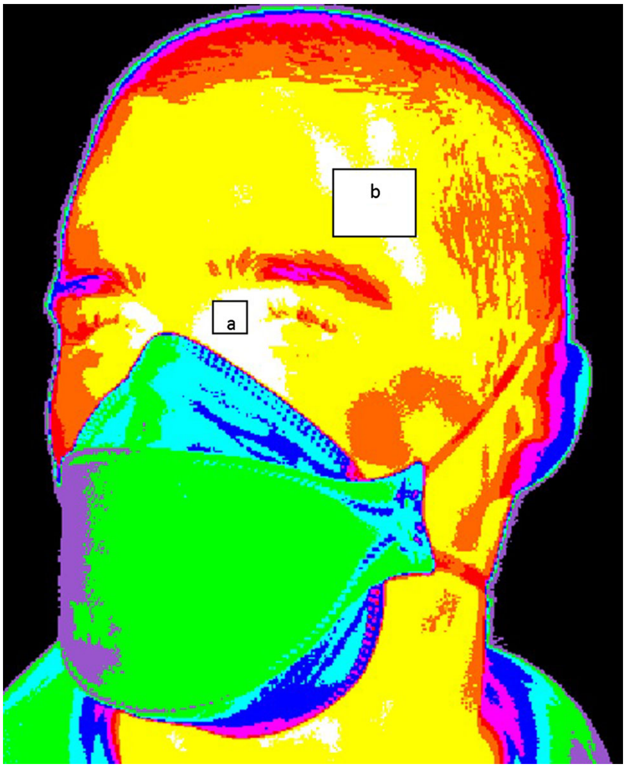

Fig. 1 Infrared thermography image of superomedial periorbital area (*a*) and superficial temporal artery area (*b*) temperature measurement sites in a right hand dominant subject

International Standards Organization (ISO) Thermal Scale (+3 = hot; +2 = warm; +1 = slightly warm; 0 = neutral; −1 = slightly cool; −2 = cool; −3 = cold) [24]. Subjects were queried as to their route of breathing (i.e., nasal, oro-nasal or oral) at baseline and during temperature measurements.

2.1 Statistical analysis

One way repeated measures ANOVA was carried out at three time points (0 [baseline], 30, and 60 min) on all dependent variables with Greenhouse-Geisser correction for a designation of statistical significance. For a variable with a significant F-ratio, post hoc pairwise comparison with Bonferroni adjustment was carried out to determine a difference between the time points. Independent samples *t* test was carried out to analyze the impact of the route of breathing (nasal vs oronasal) on SOIIBT. Statistical significance was accepted at $p < 0.05$.

3 Results

The RR did not change significantly over 1 h (F = 0.89, $p = 0.41$). The SN95 FFR deadspace temperature was significantly higher over 1 h than baseline (F = 94.37,

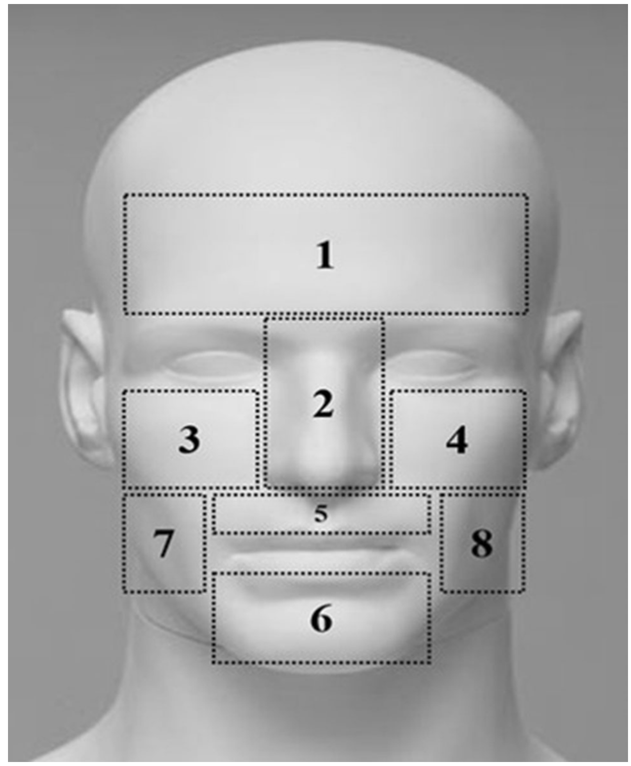

Fig. 2 Facial mannequin placard with numbered anatomic areas used for denoting regional subjective temperature changes while wearing a filtering facepiece respirator (*1* = forehead, *2* = nasal region, *3*, *4* = malar regions, *5* = upper lip region, *6* = chin area, *7*, *8* = cheeks)

$p < 0.001$), but there was no significant difference between the 30 and 60 min values. The SN95 FFR deadspace RH was significantly greater than baseline over 1 h (F = 157.70, $p < 0.001$), and was significantly greater ($p < 0.001$) at 60 min than 30 min. The temperature of the facial skin covered by the SN95 FFR increased significantly over 1 h (F = 41.83, $p < 0.001$), but no significant difference was noted between the 30 and 60 min measurements. There was no significant difference either in SOIIBT measurements (F = 0.69, $p = 0.46$) or tympanic temperature (F = 0.21, $p = 0.74$) over 1 h. Switching from nasal to oronasal breathing (n = 5) resulted in a non-significant increase in their SOIIBT ($p = 0.09$) (Fig. 3). The superficial temporal artery area temperature decreased significantly over 1 h (F = 6.18, $p = 0.008$), but there was no significant difference between the 30 and 60 min values. Thermal comfort scores rose significantly over 1 h (F = −26.08, $p < 0.001$), but no significant difference was noted between 30 and 60 min scores (Table 1). Facial areas 3, 4, and 5 (Fig. 2) were most frequently reported as becoming increasingly warm while wearing the SN95 FFR (Fig. 4).

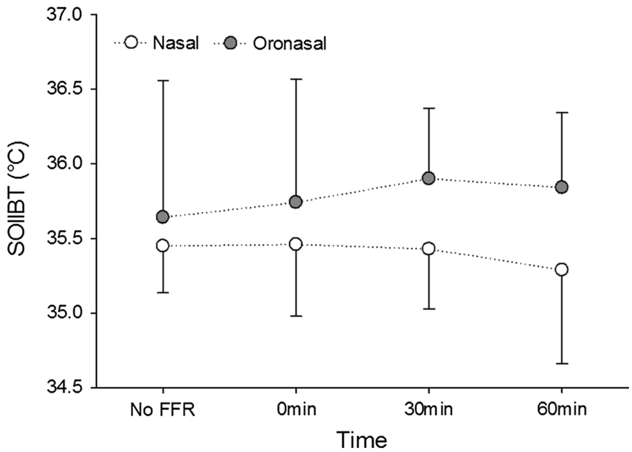

Fig. 3 Comparison of superomedial orbital infrared indirect brain temperature measurements of subjects who remained nasal breathers throughout the study (n = 10) with those who converted from being nasal breathers to oronasal breathers (n = 5) during 1 h of wearing a filtering facepiece respirator

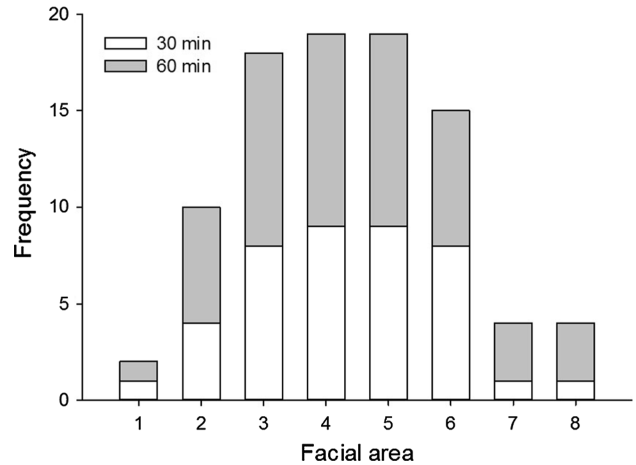

Fig. 4 Frequency distribution of facial areas perceived as experiencing increased warmth while wearing a SN95 filtering facepiece respirator at a sedentary work rate over 1 h (n = 18)

4 Discussion

The resting status of the current study's subjects, coupled with a relatively thermo-neutral environment, allowed us to isolate primarily the effect of wearing a SN95 FFR upon various indicators of body temperature. The lack of significant effect ($p = 0.41$) on the RR (Table 1) attests to the previously-demonstrated minimal impact of FFR on breathing parameters, even at low-moderate work rates [25]. The stability of the tympanic temperature measurements, throughout the study (Table 1), is evidence of the subjects' resting state and supports the recently-reported lack of clinically-significant effect of wearing an FFR upon IR tympanic membrane temperature measurements [26]. At baseline, nasal breathing was reported by 15/18 subjects and oro-nasal breathing by 3/18 subjects. At the end of 1 h of SN95 FFR use, 5/15 initial nasal breathers switched to oro-nasal breathing, and this change was associated with an increase in the SOIIBT that may have been due to loss of the recognized conditioning effect on the temperature of air passing through the nasal passages (Fig. 3) [27]. Wearing respiratory protective equipment can result in breathing pattern changes due to such factors as pressure on the nasal alae from moldable nasal bars, work rate or psychogenic issues [28]. Suggestions have been put forth that worker education in the use of such equipment should emphasize nasal breathing as the preferential route of respiration, if tolerable [28]. The mean temperatures of the facial skin covered by the SN95 FFR increased significantly ($p < 0.001$) at 30 and 60 min, and are in the temperature range at which dermal warmth receptors are activated [29]. It has previously been reported that respirator acceptability by the wearer decreases as upper lip temperature exceeds 34.5 °C [30]. The increase in the facial skin temperature in the current study coincided with increasing subjective impressions of facial warmth ($p < 0.001$) that continued to increase over 1 h of SN95 FFR use (Table 1). The facial areas most commonly affected by increased warmth were those that were most centrally located (regions 3, 4, 5)

Table 1 Mean values of measured study variables

Variable	Time		
	0 min (baseline)	30 min	60 min
Superomedial periorbital temperature	35.61 ± 0.58	35.62 ± 0.46	35.53 ± 0.61
Temporal artery temperature	35.41 ± 0.36	35.28 ± 0.41*	35.28 ± 0.46*
Tympanic temperature	36.77 ± 0.28	36.75 ± 0.26	36.76 ± 0.27
Facial temperature	32.76 ± 1.39	34.25 ± 0.92*	34.38 ± 0.71*
Thermal comfort	−0.4 ± 0.5	0.9 ± 0.9*	1.1 ± 1.1*
Deadspace temperature	26.5 ± 2.4	34.0 ± 2.5*	34.4 ± 0.7*
Deadspace humidity	20.5 ± 5.3	54.5 ± 11.2*	67.4 ± 7.6*, #
Respiratory rate	15.1 ± 2.0	14.3 ± 2.1	14.8 ± 2.4

* Significantly different from baseline

Significantly different from 30 min ($p < 0.001$)

(Figs. 2, 4). There was no significant mean difference in SOIIBT from baseline values over 1 h of SN95 FFR wear (Table 1).

The superficial temporal artery region has been touted as a reliable site for temperature determination because its perfusion is thought to be relatively constant and it is the only arterial supply of the head and face that is (generally) devoid of arterio-venous anastomoses [31]. It is thus considered by some researchers to be an accurate indicator of T_{core} [32], though this is debated by others [33]. Under temperate ambient conditions, skin temperatures will always be lower than T_{core} due to radiant heat loss through the skin and many IRT temperature studies (temporal, forehead, BTT) do not report actual skin temperatures but, rather, algorithm-derived temperature measurements that correct for ambient conditions to provide estimates of brain temperatures or other T_{core} [33, 34]. The unadjusted superficial temporal artery area mean IRT temperatures declined significantly ($p = 0.008$) with the use of the SN95 FFR, and this effect stabilized at 30 min (Table 1). This is somewhat intriguing given that the SOIIBT and tympanic temperatures remained relatively stable without significant changes noted over baseline (Table 1). However, it is recognized that superficial temporal artery region temperatures are subject to various modifying inputs (blood flow, ambient environmental conditions, sweating, etc.) [33]. It is also possible that the straps of the SN95 FFR, which traverse the superficial temporal artery region, may have compressed the vessel somewhat and altered its flow and perfusion characteristics. In a study utilizing the highest value of frontal area IRT temperatures of 99 clinic patients who had a mean tympanic temperature (36.6 °C) similar to that of the current study, wearing a surgical mask was associated with a 0.5 °C decrease in IRT [35]. The baseline superficial temporal artery region temperatures in the current study mirror closely the findings from a prior IRT study of 1517 subjects [36].

The superior ophthalmic vein (SOV), the largest orbital vein and principal route of orbital venous drainage, is formed by the union of the supraorbital and angular veins at ~6 mm posterior to the superior sulcus of the eyelid [37]. The SOV flows from the superior medial orbit region through the superior orbital fissure to empty into the cavernous sinus [38]. The length of the SOV is variable (due to the variability in the depth of the human orbit), but recent cadaveric research has shown an average length of 49.2 ± 16.2 mm (range 33.9–65.7 mm) [14]. The SOV is insulated somewhat from heat loss along its course because it is layered between the superior rectus muscle and a fascial hammock-like sling formed by connective tissue septa of the medial, superior and lateral rectus muscles' suspensory systems [39]. The SOV is thus thought to serve as a thermal conduit for the temperature of the cavernous sinus blood that is in equilibrium with brain tissue [15] in accordance with Fournier's Law of Heat Conduction (i.e., heat flows from regions of higher temperature to lower temperature along the temperature gradient).

Under normal conditions, average brain temperature is ~0.3 °C higher than other T_{core} sites [40], due to the relatively high metabolic rate of the central nervous system, and reflects a balance between heat production from cerebral metabolism and heat removal primarily by cerebral blood flow [41]. This high convectivity of heat between brain tissues and capillaries allows removal of the 0.16 °C/min heat generated by the brain [11]. Arterial blood supplied to the brain and body is cooled primarily by the venous blood from the skin [10] with a minor component of cooling (≤0.1 °C) via heat exchange from the lungs [41, 42] that is dependent on the level of ventilation. The brain as a whole does not exhibit one global temperature because the regulation of brain temperature depends primarily on the temperature of the incoming cerebral arterial blood flow [40]. Thus, brain areas with high blood flow (i.e., cortex) have lower temperatures than areas with lower blood flow (i.e., white matter) [43]. In general, the center of the brain is from 0.5 to 1.0 °C warmer than the epidural space [44]. Data on cavernous sinus temperatures are sparse, but experiments with horses at rest (ambient conditions 19 °C, 25 %RH) have indicated a 0.9 °C lower temperature in the cavernous sinus compared with the cerebrum [45]. The SOV likely is more reflective of brain superficial cortical temperature rather than deeper brain structures inasmuch as the inferior and superficial medial cerebral veins that flow into the cavernous sinus drain the superficial areas of the brain [12].

The inner canthus of the superomedial periorbital region of the eye is consistently the warmest area on the head [34] due to its vascularity (fed by the ophthalmic artery, a branch of the internal carotid artery), thinness of the overlying skin (enhanced radiant heat loss) and concavity (inhibits cooling effects of ambient airflow on the skin) [46]. The SOIIBT in the current study mirrors previously-reported data for similar sedentary states without respirator use [36, 47, 48], thereby further suggesting that the SN95 FFR had no impact on the SOIIBT. It is also interesting to note that the 0.3 °C higher temperature of the brain temperature surrogate (i.e., SOIIBT) compared with the unadjusted T_{core} surrogate (i.e., superficial temporal artery area temperature) in the current study is the same as the reported usual difference between average brain temperature and other T_{core} in invasive studies [40]. The present study findings indicate that wearing a SN95 FFR at rest for 1 h did not result in an increase in brain temperature, as indicated by the SOIIBT. This suggests that complaints of respirator-associated thermal discomfort are more likely related to thermal sensations of the facial skin covered by

the protective facemask. Increases in the temperature of the skin covered by a protective facemask activate facial skin warmth receptors (consisting of free nerve endings of unmyelinated C-fibers). These receptors then direct afferent nerve impulses to the central nervous system via sensory fibers of the three divisions of the trigeminal nerve to its spinal nucleus and then to the post central gyrus of the parietal lobe cortex of the brain [49]. The SOIIBT noted in the current study is not the actual brain temperature (due to dampening effects on the SOV of the facial skin circulation), but may indicate a normal superficial cortical brain temperature in young, healthy adults in a resting state. However, this supposition will require significantly greater numbers of subjects to fully verify. Prior IRT investigation has reported that a superomedial canthus temperature of 36.3 °C is the optimal temperature to maximize sensitivity (85.4 %) and specificity (95 %) for fever screening [50].

Limitations of the current study include the relatively small number of subjects tested (n = 18). Our findings should not be extrapolated to children, inasmuch as an IRT study of 173 afebrile children (ages 1–17 years) determined an unadjusted mean orbital region temperature of 36.61 °C (calculated from a rectangular area encompassing both eyes) [51]. The most accurate non-invasive assessment of brain temperature is by measurement of the latency of auditory-evoked brain potentials (as these are impacted by brainstem temperature); a prior investigation has noted no impact of breathing warm air on brain temperature [52]. We only tested one model of FFR (3M 1870 flat-fold model) and cannot comment on other models that might have larger respirator deadspaces, or on other classes of negative pressure respirators (e.g., elastomeric air-purifying respirators). Higher ambient temperatures and high workloads resulting in increased ventilation of warmer air could theoretically result in brain warming, but this remains speculative and requires further investigation.

5 Conclusions

The use of a SN95 FFR at rest over 1 h did not result in brain warming, as indicated by the SOIIBT. However, the increase in SOIIBT noted in the minority of subjects who switched from nasal to oro-nasal breathing over 1 h suggests that the route of breathing may impact SOIIBT measurements. Reported increases in warmth sensations with wearing FFR are likely due to the barrier effects of the device upon heat release mechanisms of facial skin (convection, radiation, evaporation) that result in increased dermal afferent sensory signals to the brain via branches of the trigeminal nerve. Efforts at relieving the perceptions of increased thermal discomfort with protective facemasks should look into measures that result in cooling of the covered facial skin utilizing technologies such as mini-fans, improved exhalation valves, phase change materials, etc. [3]. Further research into SOIIBT is also warranted to develop guidelines determining febrile states and optimizing its use in such areas as medicine, sports and exercise regimens.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Informed consent The study was approved by the NIOSH Institutional Review Board and all subjects provided written and -verbal consent.

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